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RILEM TC 154-EMC - ELECTROCHEMICAL TECHNIQUES FOR MEASURING CORROSION IN CONCRETE

Progress Report 1994-97

Prepared by C. Andrade

1. INTRODUCTION

During the last two decades, the corrosion of reinforcement has become the highest concern regarding concrete durability. Premature deterioration due to concrete cracking and spalling induced by rebar corrosion is focusing the attention of an increasing number of researchers and related specialists, due to the high economic consequences and the lack of definitive technical solutions.

Numerous related subjects are being developed around rebar corrosion. Thus, the search for additional methods to protect the steel (galvanizing or epoxy coatings), or the use of corrosion inhibitor admixtures or cathodic protection, are examples of related aspects which require testing and development. The use of a wide variety of new materials for repair, as well as the application of high resistance concrete to overcome or delay the consequences of the corrosion, are other areas which have grown up around this durability problem.

Of all these areas, the techniques to measure the corrosion risk are among the most important, because non-destructive appraisal of the corrosion evolution is a necessary tool for the previous assessment of the importance and location of the distress.

However, despite the crucial role that these measurement techniques play in the assessment of such problems, very little attention has been given to their standarization. Apart from ASTM, which has a set of standards dealing with metallic corrosion (G3-89, G5-87, G57-78, G59-91, G102-90, G109-92) and with rebar corrosion (C-876 and G-109-92), only other isolated and more local examples exist.

RILEM was the first international organization to publish documents trying to explain corrosion mechanisms and the most appropriate methods of protection. The first RILEM Technical Committee in this field, TC 12-CRC, "Corrosion of Reinforcement in Concrete", was set up in 1960. This Committee prepared the first comprehensive State-of-the-Art report, published in 1976.

A second Committee, TC 60-CSC, "Corrosion of Steel in Concrete", was established in 1980 and chaired by P. Schiessl. A State-of-the-Art report was prepared to present the agreed knowledge about the phenomena involved. Later, in 1988, another Committee was established and was also chaired by P. Schiessl: TC 124-SRC, on "Strategies for the Repair of Concrete Structures damaged by Steel Corrosion". The TC's final report contains the methodology for the selection of the repair process and the description of the most important methods. Reference was also made to the importance of the evaluation techniques and a short description of some of them was included.

The present RILEM Committee, TC 154-EMC, "Electrochemical Techniques for Measuring Metallic Corrosion in Concrete", is a natural continuation of previous RILEM work. The first meeting was held in 1992 although the work effectively started in 1994. Time was taken to prioritize the objectives and to select the type of final products to be produced by the committee. It was decided that the more important techniques to address were those to be applied on-site. Finally, it was decided to write three Recommendations on:

- Half-cell potential measurements - potential mapping measurements.
- Corrosion rate measurements by means of polarization resistance.
- Embedded sensors.

In a second step, other two techniques may be considered:

- On-site electrical resistivity measurement.
- Laboratory evaluation of corrosion inhibitor efficiency.

In this Progress Report, the state of the work on the first three Recommendations is summarized.

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2. HALF CELL POTENTIAL MEASUREMENTS - POTENTIAL MAPPING TO LOCATE CORRODING REINFORCEMENT IN CONCRETE STRUCTURES

Prepared by B. Elsener

2.1. Scope

This recommendation provides the background and a description of the application and guidelines for the interpretation of half cell potential measurements in order to locate, in a non-destructive way, corroding rebars on reinforced concrete structures. It covers both the point measurements and the potential field measurements.

2.2. Significance and use

Half cell potential measurements are recommended and may be used for one of the following main purposes:

1. To locate corroding rebars and thus assess the present corrosion condition of the reinforcement during inspection.
2. To define the position for further destructive analysis (cores for chloride analysis, inspection windows to control the corrosion state of the rebars, etc.) on the basis of the results of potential measurements.
3. To control the corrosion state of the rebars after repair work and thus evaluate the efficiency of repair work.
4. To design an anode layout of cathodic protection systems or electrochemical restoration techniques.

Half cell potential measurements do not provide information on the corrosion rate of the rebars. The results should be interpreted by specialists or skilled engineers experienced in the field of corrosion testing and structural evaluation.

2.3. Theoretical background

Corrosion of steel in concrete follows the normal electrochemical mechanism of corrosion of a metal in an electrolyte. According to the Pourbaix diagram, ordinary reinforcing steel in the highly alkaline environment of concrete is protected by a thin oxide film (the passive film) from further corrosion. This protective passive film may be destroyed by chlorides penetrating through the concrete cover to the steel surface and/or by carbonation of the concrete. Corrosion will take place when the steel is depassivated and both oxygen and humidity are present at the steel surface. Half cell potential measurements can detect only active corrosion. Rusted rebars in dry concrete will appear as non corroding.

The corrosion may be generalized or localized. A macrocell corrosion can also be produced due to the high electrical resistivity of concrete.

2.3.1. Half cell potentials and reference electrodes

The corrosion potential Ecorr (half cell rebar/concrete) is measured as a voltage difference against a reference electrode (half cell). The experimentally measured potential difference between the steel in concrete and the reference electrode will depend on the type of reference electrode used and on the corrosion condition of the steel in concrete. In addition, half cell potentials of steel in concrete cannot be measured directly at the interface of the rebar due to the concrete cover; the potentials are thus influenced by the macrocell currents and possibly by junction potentials.

For site work, the saturated copper sulphate electrode is most robust and is sufficiently accurate. Calomel and silver chloride electrodes are more often used in laboratory work. The temperature dependence of the reference electrodes has no practical influence on the readings on site.

In the case of macro-cell corrosion and localized attack, the reference electrode at the concrete surface does not measure the "true" corrosion potentials of anode and cathode, but rather a mixed value depending on the position of the electrode. As is shown in Fig. 1, the most negative values of the half cell potentials always locate the anode. The absolute values of the potentials measured are influenced by the cover depth and the resistivity of the concrete.

Further factors influencing the distance of macrocell action are the availability of oxygen at the cathode (cathodic current density) and the amount of passive rebar surface around the anode.

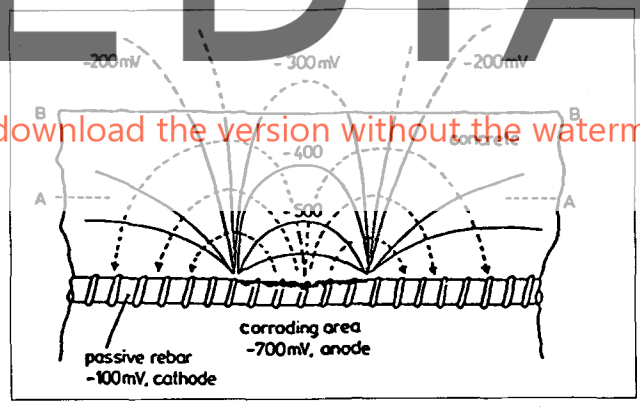

Fig. 1.

2.4. Measurement procedure

The primary goal of potential measurements on reinforced structures is to locate areas of corroding reinforcement. Thus, before starting to take measurements, a coordinate system has to be put onto the structure in order to relate readings with the point on the structure where they were taken. The coordinate system may be oriented towards characteristic features or consist of lines sprayed onto the concrete surface. For measurements in the project phase (point measurements), a large grid (0.5-2m) may be enough.

Other further aspects to be considered are: to provide a correct electrolytic contact to the concrete surface by

means of a proper wetting and a sound electrical contact to the steel reinforcement.

For potential field measurements (large number of data, small grid size), the optimum way of representing the data has been found to be a colour map of the potential field (Fig. 2), where every individual potential reading can be identified as a small square dot. Contour plots are more difficult to read and are affected by erroneous measurements, and thus are not recommended.

Statistical representation of the data (cumulative frequency plot, histograms) provides an indication of the percentage of corroding reinforcement on a structure.

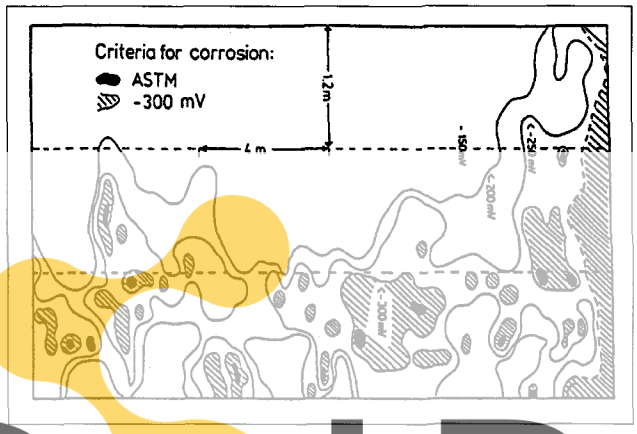

Fig. 2.

2.4.1 Factors influencing the measurements

The factors influencing the half cell measurements are affected by the resistivity of the concrete, the temperature, the chloride content and the pH of the pore solution (carbonation).

2.5. Interpretation of half cell potential data

Location of corroding rebars is best achieved by considering the spatial variation of potential (gradients) and not the absolute values of the potentials, as has been shown by a great deal of research work and practical application of potential mapping. In contrast to ASTM C876-91, universal fixed boundary limits of potentials to distinguish active and passive zones are not applicable. The statistical plot of the results is also an excellent tool to distinguish active from passive zones.

The half cell potentials can be also related to the degree of damage and the chloride content in a particular structure.

3. TEST METHODS FOR ON-SITE CORROSION RATE MEASUREMENT OF CONCRETE REINFORCEMENTS BY MEANS OF THE POLARIZATION RESISTANCE METHOD

Prepared by C. Andrade and C. Alonso

3.1. Scope

The recommendation covers the description of methods for the estimation in large size concrete structures of the instantaneous corrosion current, Icorr, in $\mu A/cm^2$, by means of the Polarization Resistance technique, Rp.

The values of Icorr can be used for assessing the rate of degradation of concrete structures affected by reinforcement corrosion. However, this does not provide information about the actual steel cross-section loss, which can only be assessed at present by means of visual observation.

3.2. Significance and use

The test methods described are suitable for on-site evaluation of concrete structures. They cannot be applied to submerged elements and to structures or elements affected by stray currents. In fully sea water-saturated structures, the interpretation of the results is still under discussion.

The Icorr results obtained by the test methods may be used for one of the following purposes:

1) To assess the present corrosion condition of the reinforcement, that is, to identify corroding/non-corroding zones.

2) To evaluate the efficiency of repair work.

3) To calculate the loss in bar diameter (attack penetration) Px. Consequently, the Icorr values can be implemented into structural models to enable engineers to make an assessment of the future evolution of structural performance, cover cracking, loss in bond and loss in load-bearing capacity.

The corrosion current values should be interpreted by specialists or skilled engineers experienced in the field of corrosion testing and structural evaluation.

3.3. Definitions

The terms defined in the Recommendation are:

– The Polarization Resistance, Rp, (Fig. 3) distinguishing the Apparent Value (not referred to any area of the reinforcement) from the True Rp which is referred to the area polarized by the electrical field.

– The critical length, L_{crit}.

– The instantaneous corrosion current density, i_{corr} in $\mu A/cm^2$.

– The corrosion velocity, v_{corr} in mA/year.

– The representative value of i_{corr} and v_{corr}.

– The penetration of attack, P_x.

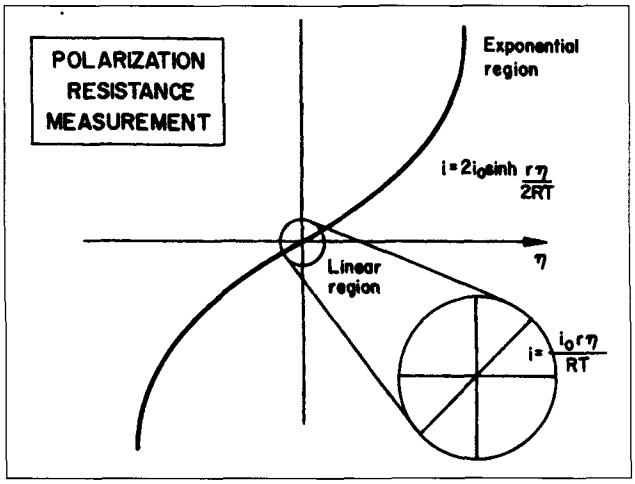

Fig. 3.

– The pit concentration factor, α.
– The maximum pit depth, P_{pit}.
– The reinforcement diameter loss, $\varnothing_x$.

3.4. General considerations on the Rp Technique for on site measurements

The main considerations for the correct measurement of Rp in metals embedded in concrete are:
1) Compensation of IR drop.
2) Verification of the range of linearity around the Ecorr.
3) Achievement of a certain stationary state.

Beside these basic aspects of the measurement of the Rp, the main characteristic, about size dependency regarding the corrosion monitoring, is the quasi-infinite length of the rebar. This circumstance calls for using methodologies not affected by the rebar size or able to calculate the metallic surface polarized during the measurement.

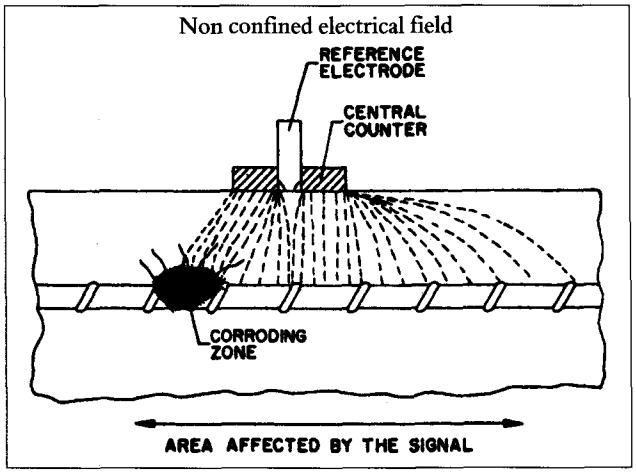

Fig. 4.

In small specimens, the uniform distribution of the current applied between auxiliary and working electrodes is usually guaranteed. However in large structures, the auxiliary electrode is much smaller in size than the working electrode (the rebar). This situation gives rise to a non-uniform distribution of the current along the reinforcement, as shown in Fig. 4. The electrical signal tends to vanish with the distance from the auxiliary or counter electrode, CE. The required uniform distribution is, therefore, not met and the $\Delta E/\Delta I$ slope cannot be referred to a specific rebar surface.

In consequence, either the critical length reached by the electrical field has to be calculated or the current confined to a delimited area (Fig. 5).

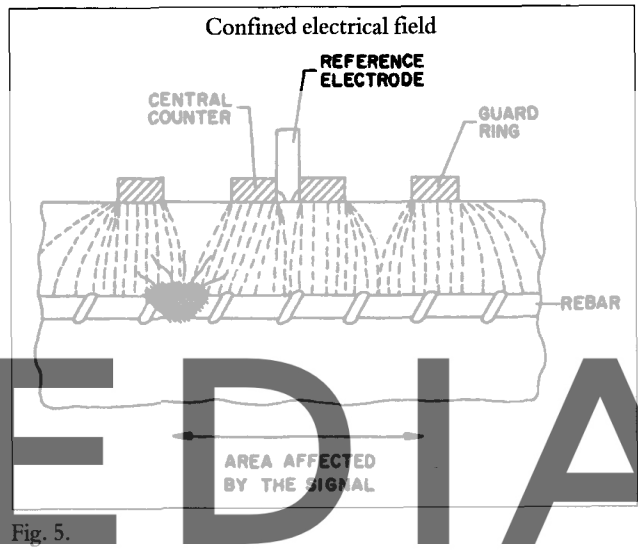

Fig. 5.

3.5. Methods for on-site measurement of the corrosion rate

In order to solve the uncertainty of the rebar surface really polarized by the current, the methods of measurement developed until now are based on the following principles:

a) The calculation of the critical length reached by the current when applied from a small auxiliary electrode placed in the surface of the concrete. Among them can be mentioned:
– Multiple electrode method (stationary)
– Galvanostatic pulse (non stationary)

b) The use of very big auxiliary electrodes, which minimize the effect of the critical length (stationary).

c) The confinement of the current to a predetermined area by means of a guard ring (stationary) (Fig. 5).

These methods are briefly described in the text of the Recommendation.

3.6. Practical execution of measurements

The aspects addressed are related to the characteristics of:
– the apparatus,
– the auxiliary sensor,
– the contact device between auxiliary sensor and concrete surface,
– calibration and standarization of the apparatus,
– reference electrodes.

The need to perform measurements comparing the particular equipment to a standard laboratory potentiostat is also described. This standarization is needed in order to verify that the value of the Rp measured with the portable device is within a scatter of a factor of 2, with regard to the reference value measured with a laboratory potentiostat. The precision and bias are also delimited.

Further, the aspects dealing with the practical procedure of measuring on-site are described: the concrete surface conditions regarding its humidity content, the connections between equipment and structure, and the frequency of the measurements.

3.7. Interpretation of measurements

Expressing the quantities in mm/year, the following classification has then been established:

Vcorr (mm/year)	Corrosion level
< 1	negligible
1 - 5	low
5 - 10	moderate
> 10	high

The Icorr values do not always remain constant. The variation is due to:
– the evolution of the corrosion process itself, which continuously generates rust and may induce cover cracking;
– the influence of environmental actions such as the climatic parameters relative humidity, RH, and temperature, T°.

In submerged structures, the Icorr values may remain fairly constant because they do not suffer from external temperature changes. The same happens in indoor structures with controlled climatic conditions. In all the other cases, the Icorr is a function of the climatic parameters.

The document ends with the description of the different applications of the corrosion current values and of the data presentation report.

4. MEASUREMENTS WITH EMBEDDED SENSORS
Prepared by Ø. Vennesland

4.1. Scope

Measuring with embedded probes may have several purposes. The type and number of probes will depend on these aims. Examples of applications are to:
– Follow the effectiveness of a repaired structure or of a surface treatment.
– Monitor the advance of the carbonation front or of the chloride threshold.
– Detect the beginning of reinforcement corrosion.
– Control a cathodic protection installation.

4.2. Types of measurements

The variables which can be measured at present by means of suitable electrochemical embedded sensors are:
– Electrochemical potential
– Corrosion rate
– Resistivity and electrical resistance
– Oxygen availability
– Temperature
– Macrocell current
– Chloride content and carbonation
– Humidity variations

The further paragraphs develop the different sensor types that exist at present to measure any of these variables. Aspects such as robustness, durability (stability), cost and accuracy are briefly addressed. The need for calibration of the probes is also discussed.

The final part considers the location of the sensors regarding the selection of critical areas and the optimization of the number of readings with regard to the aim of the measurements.